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Capt. Edmund B. Weis, Jr., USAF, MC; Capt. Neville P. Clarke, USAF, VC; and James W. Brinkley

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13. ABSTRACT

The results of this testing indicate a set of impact conditions which are tolerable. The tests have been performed in such a way as to have a maximum of generality. The influence of the restraint system and the helmet are quantitatively unknown factors.

There is considerable indication that the head will present a problem in tolerance to impact acceleration patterns as more severe exposures are investigated. There is, however, no basis in these results for a forecast of any probable or absolute injury level.

Preliminary results of a mathematical analysis have been presented, and the trends indicate that it is desirable to attenuate high-frequency components of the acceleration pulse in impact protection.

The power density spectrum of the input accelerations have been presented and discussed as a method of approaching the problem of determining the tolerability of an arbitrary acceleration pattern.

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Human Response to Several Impact Acceleration Orientations and Patterns

CAPT. EDMUND B. WEIS, JR., USAF, MC, CAPT. NEVILLE P. CLARKE, USAF, VC
and JAMES W. BRINKLEY

THE EVALUATION of human responses to abrupt accelerations under controlled experimental conditions has been almost entirely limited to studies involving exposure of subjects to forward ($+a_x$), backward ($-a_x$), headward ($-a_z$), and footward ($+a_z$) acceleration.[4,5,6] The situations, other than controlled experiments, in which humans are exposed to high-magnitude, abrupt accelerations associated with large changes in velocity usually occur under emergency conditions. In the case of emergencies occurring during aerospace flight, escape from the parent vehicle usually involves exposing crewmen to acceleration environments in which only the initial force ejecting the man from the vehicle acts in a predictable direction. For most of the other parts of the sequential acceleration environment, the direction of the acceleration vector with respect to the crewman is, at least to some extent, uncontrolled. In other cases, such as ground landing impact in closed capsules, the orientation of the acceleration vector is random, depending on the direction of the surface wind. The studies mentioned above have shown that orientation of the acceleration vector is a major factor in determining the response of man to a given load, since the critical body structures involved and, presumably, man's dynamic response characteristics vary with the direction of the applied force. Since the orientation of the acceleration vector is variable under operational conditions and since the effects of acceleration are dependent on this orientation, the National Aeronautics and Space Administration, Manned Spacecraft Center (NASA-MSC), and the Aerospace Medical Research Laboratories (AMRL) have begun a jointly sponsored research effort to systematically explore the effect of variations of orientation and acceleration pattern on the response of man to abrupt acceleration. Seventy-five experiments in pursuit of this problem are reported here.

In these experiments, the subject, wearing the Mercury pressure suit helmet, was placed in a rigid vehicle in a sitting position, restrained with a non-extensible chest and pelvic harness, and exposed to six deceleration profiles in seven orientations. In the six acceleration profiles peak G ranged from 3 to 26 G units, impact velocity ranged from 5 to 28 feet per second, and onset ranged from 200 to 2000 G units per second. The seven orientations contained forward, upward, right and left components of acceleration and were 45° apart. The acceleration of the center of gravity of the vehicle, the force exerted by the subject on the vehicle, and biomedical data were recorded.

The force and acceleration data from these experiments have been subjected to considerable mathematical analysis in order to abstract the body dynamic response. The methods and meaning of this analysis will be presented briefly and some preliminary results presented and discussed.

METHODS

The laboratory test facility used in these experiments is the AMRL Vertical Deceleration Tower (Fig. 1). This facility is a guided free-fall device with a controlled deceleration produced by a plunger which

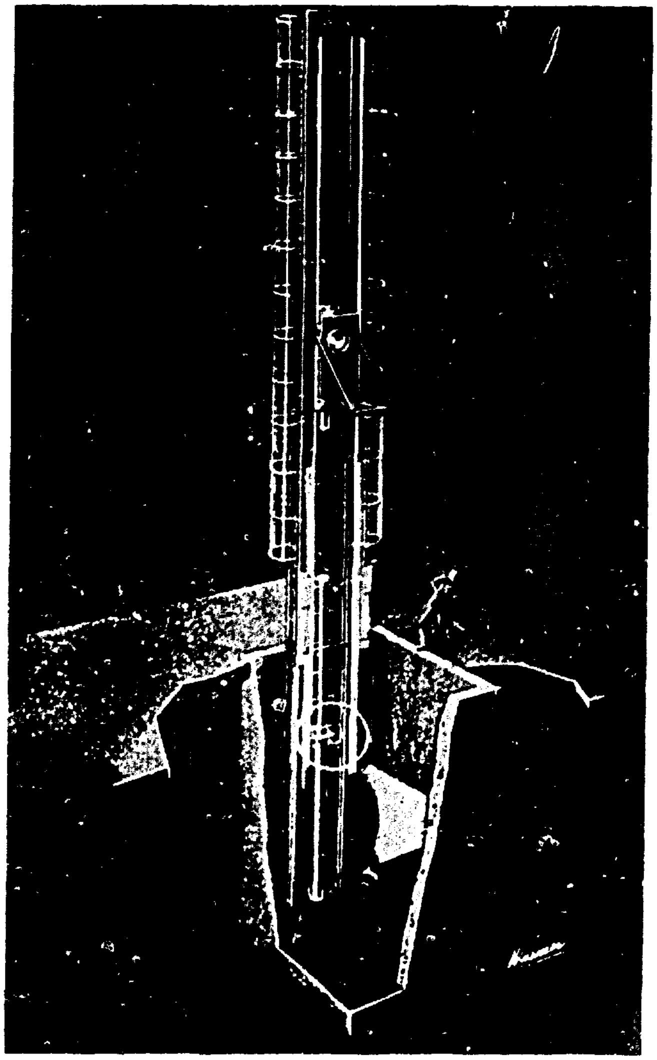

Fig. 1. Decelerator tower.

From the 6570th Aerospace Medical Research Laboratories.
Presented at the annual meeting of the Aerospace Medical Association, Los Angeles, California, April 30, 1963.

displaces water from a cylinder. The entry velocity is controlled by the drop height. The deceleration pattern is controlled by the plunger shape. The deceleration pattern (Fig. 2) is readily reproduced. A triangular

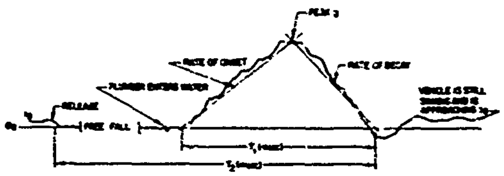

Fig. 2. Generalized acceleration history.

approximation to the impact portion of the wave form is also indicated.

A vehicle was suspended from three (Fig. 3) or

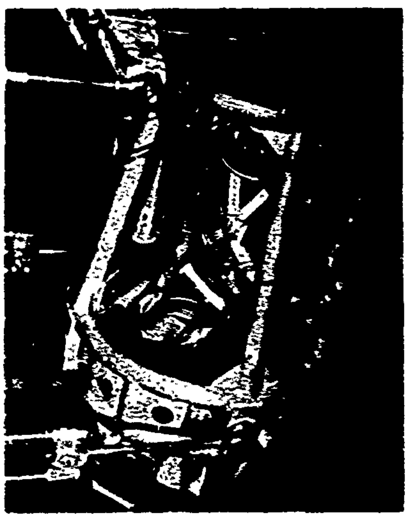

Fig. 3. Omnidirectional vehicle.

four (Fig. 5) points on a cantilever assembly attached to the deceleration tower cart. Each suspension connection was made through a load cell which measured the instantaneous force at that point. The vertical

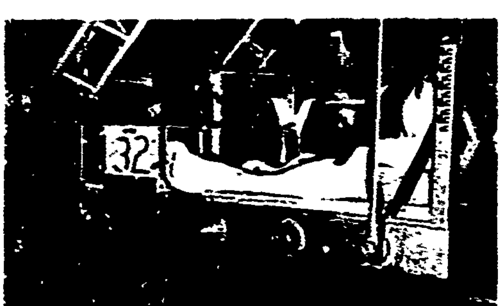

Fig. 5. Lateral vehicle.

axis of the center of gravity for each orientation of each vehicle was determined by static measurements and an accelerometer was mounted on this axis.

The physical instrumentation system uses the accelerometers and load cells mentioned above as transducers. These are excited by carrier wave amplifiers whose outputs are fed to galvanometer drivers which activate both light galvanometers in an oscillograph and a frequency modulated magnetic tape recorder. System tests indicate a frequency response flat (within 5 per cent) to 200 cycles per second and a static and dynamic accuracy of 5 per cent.[7]

The biomedical instrumentation system uses a Sanborn 150 series six-channel hot-pen recorder for the electrocardiogram and respiration. A standard clinical five-lead electrode system is used for the electrocardiogram, and leads I, AVF, and V2 are monitored continuously during testing. During early tests the vectorcardiogram was recorded by a polaroid camera from an oscilloscope, but this recording was discontinued when no changes were noted.[7]

Black and white 16-mm. motion pictures of each test were made at 400 frames per second.

The primary vehicle used in these tests is shown in Figure 3. This omnidirectional vehicle was designed to fit 5th to 95th percentile subjects. The structure, exclusive of suspension, has a back angle of 0°, a thigh-to-torso angle of 78°, and a variable thigh-to-leg angle with a mean of 78°. It is provided with lateral head supports. The suspension of this vehicle is designed to provide infinite variation in the back inclination and 22.5° increments from left to right lateral.

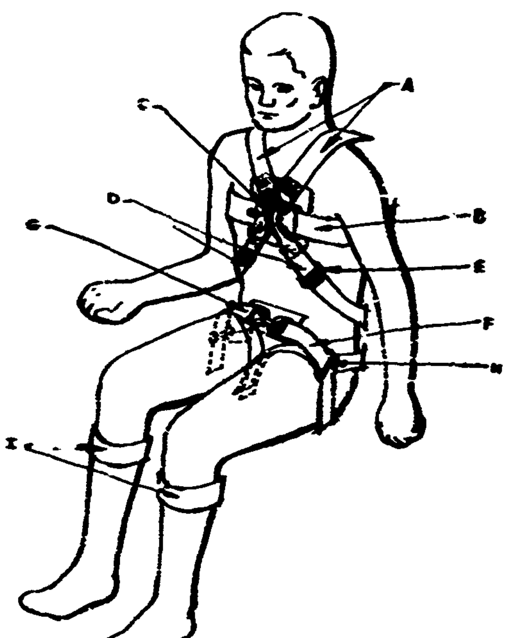

Fig. 6. Restraint system.

In the early stages of testing, a body support frame was designed for lateral orientation, as shown in Figure 5.

The restraint system used is shown in Figure 6. The chest complex consists of a chest belt and two shoulder-to-flank belts fastened with a safety belt latch anterior to the sternum. The pelvic complex consists of a continuous belt on each side which starts between the thighs, passes through a slider at the hip (which is fastened to the seat and back), and connects with the other side over the pubis in a snap latch. The leg is restrained at the calf with another belt. A materials list with the letters referring to those in Figure 6 is presented in Table I.

TABLE I. MATERIALS LIST

A	3" type IV "Dacron" web shoulder straps
B.	3" type IV "Dacron" web lateral chest straps
C.	Safety belt latch assembly with integral adjusters
D.	2" type III "Dacron" web torso straps
E.	Harness adjuster
F.	2" type III "Dacron" web lap belt and "Y" tie down straps
G.	Parachute harness snap latch with integral adjusters
H.	Bar adjuster
I.	2" type III "Dacron" web leg straps

The restraint system used on the earlier lateral body support frame was similar to that described above except that an eight-inch vest was used instead of a three-inch belt on the chest and that the thigh and lap belts were not integrated.

The support system in the omnidirectional vehicle was the structure itself. In the lateral body support frame both rigid foam couches and semi-rigid "microballoon" couches were used. In each case the couch was molded closely to the body contour in the form of a lateral-body cast from the knee to the head. The "microballoon" couch is a thin rubber bag filled with small spheres. When the bag is evacuated, the spheres form a semirigid contour because of the constraint of the bag and friction between the spheres. These couches were used in the initial lateral studies to aid in defining the problems involved. They were not used in the omnidirectional studies because of experience and confidence gained from the early tests and because of the desire to eliminate them as variable factors.

The Mercury pressure suit helmet was used in all tests. The helmet was used as designed in the lateral body support frame tests and in the early tests in the omnidirectional vehicle. For reasons to be described later, the helmet was modified by removing the earphones to achieve a closer fit with vinyl foam inserts. The helmet was initially unrestrained, but was restrained during later tests for reasons discussed below.

The subject panel consisted of 20 male Air Force personnel. Each had a Class III flying physical within the last 6 months, x-rays of the skull and spine, double master's electrocardiogram, routine urinalysis and detailed neurological examination. Immediately before and after each test, the subject was given a cursory neurological examination and the blood pressure was taken. Immediately post-test the subject was asked the following questions.

(1) What are your general comments about the test?
(2) Do you have any pain?
(3) Did you have any particular problems with any part of your equipment?
(4) Did you notice any particular motion within or about yourself?
(5) How do you compare this test with your previous experience?
(6) Would you repeat this test now?
(7) Do you have any residual effects from the test? (24 hours post-test)

Twenty-four hours post-test a routine urinalysis was accomplished.

The mathematical analysis is based on the Fourier Transformation. This technique is basically an extension of Fourier harmonic analysis to transient situations; that is, the force and acceleration data is resolved into corresponding frequency components. The dynamic response information is derived by finding the ratio of the Fourier Transforms of force to velocity (derived from the acceleration). This, essentially, means that the relationship (phase and magnitude) between corresponding frequency components of force and velocity is established. The justification for this analysis is the assumption that the subject's dynamic response is qualitatively similar to that of a linear, second order, spring-mass-damper system. The relationship (called mechanical impedance) between force and velocity in a linear mechanical system is uniquely expressed by the transformation technique described above, and the impedance so defined is a unique function of the spring-mass-damper parameters of the mechanical system.[1,2,3]

The magnitude of the Fourier Transform of the acceleration is, in fact, a representation of the amounts of all frequency components in the pattern and is the square root of the power density spectrum, which is meaningful in terms of the energy input to a linear mechanical system.

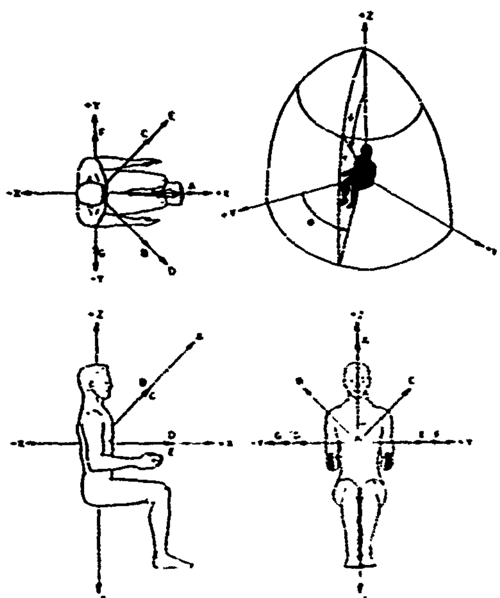

Fig. 4. Orthographic views of the orientation.

TESTING

The orientations studied have been chosen so that the acceleration vectors are not more than 45° apart. The description of the orientation refers to the direction of the impact acceleration vector with respect to a coordinate system in the sitting man. This coordinate system has the Z axis parallel to the spinal axis, the Y axis parallel to a line through the shoulders, and the X axis mutually perpendicular. The orientations and the coordinate system are shown in Figure 4. The designations of the test orientations are given in Table II in a standard spherical coordinate system notation

TABLE II. ACCELERATION ORIENTATIONS

Vector	Orientation	Phi	Theta
A	Up 45°	0°	45°
B	Up 45° Right 45°	315°	45°
C	Up 45° Left 45°	45°	45°
D	Right 45°	315°	90°
E	Left 45°	45°	90°
F	Left 90°	90°	90°
G	Right 90°	270°	90°

(phi, theta) and in a modified spherical coordinate system proposed by NASA-MSC which uses direction qualifiers with the angles. In the latter system the X-Y plane is the origin of the up-down angles which vary from 0 to 90°. The X-Z plane is the origin of left-right angles which vary from 0 to 180°. For analysis purposes, the standard spherical notation is somewhat less ambiguous.

Considering the capability limitations of the vertical deceleration tower, the acceleration profiles have been chosen so that there is a gradual increase in impact velocity and peak G. Rise time was graduated to the extent possible. Examples of the six acceleration profiles used are shown in Figure 7.

The tests conducted are best described in tabular form. Table III indicates tests done with the lateral body support frame on microballoon couches, and Table IV-A indicates tests done in the omnidirectional vehicle. In these tables T_1, T_2, peak G, onset, and decay

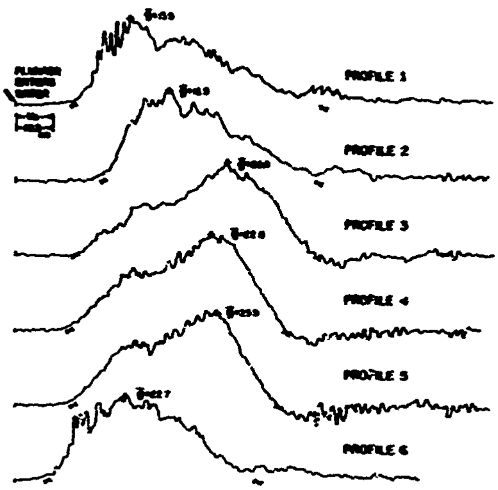

Fig. 7. Omnidirectional vehicle acceleration profiles.

TABLE III. LATERAL VEHICLE TESTS

Date	Drop No.	Name	T_2 (m sec.)	ΔV (ft./sec.)	Peak G Units	Onset (G/sec.)	Decay (G/sec.)	T_1 (m sec.)
Left Lateral—Right 90°								
9- 8-62	760	WS	397	8	4.87	62	62	97
9-10-62	761	WS	465	12.75	10.66	222	222	48
9-10-62	762	AR	571	12.9	4.27	171	46	163
9-11-62	763	AN	387	9.15	5.04	313	70	98
9-11-62	764	AN	465	13.4	9.86	211	34	31
9-11-62	765	ES	675	14.75	4.42	545	296	210
9-12-62	766	PS	547	14.6	8.7	268	207	108
9-12-62	767	MS	600	18.1	8.97	360	236	61
9-12-62	768	EN	703	18.5	9.3	121	181	103
9-13-62	769	WM	573	22.5	11.7	530	308	72
9-13-62	770	WS	561	22.5	12.3	397	286	64
9-14-62	771	EI	510	21.9	13.9	302	515	74
9-14-62	772	CM	640	23.5	15.2	720	465	71
9-17-62	774	MN	536	15.4	14.5	727	525	43
9-26-62	806	AR	548	16.7	15.1	590	795	36
9-26-62	807	PE	585	17.35	16.6	975	755	29
9-26-62	808	CT	648	20.3	21.6	1350	1029	36
Right Lateral—Left 90°								
9-17-62	775	LG	[illegible]	9.25	5.62	400	92	75
9-18-62	876	TE	[illegible]	9.25	5.21	323	[illegible]	100
9-18-62	777	TE	[illegible]	13.5	8.24	374	175	67
9-19-62	778	WS	469	13.0	9.57	478	[illegible]	62
9-19-62	77[illegible]	CT	550	13.9	8.23	200	310	101
9-20-62	[illegible]88	PE	628	17.35	9.77	443	174	79
9-20-62	789	ES	700	19.85	9.6	343	168	117
9-20-62	790	WT	733	20.6	11.1	550	118	121
9-20-62	791	MS	683	20.6	12.4	564	364	67
9-21-62	792	EN	660	18.1	14.8	224	532	91
9-21-62	793	WM	795	21.9	14.8	550	224	92
9-21-62	794	AN	544	15.7	13.5	614	436	53
9-24-62	801	PS	551	16.7	14.85	782	875	34
9-25-62	802	TE	584	18.1	14.0	845	763	41
9-25-62	805	LG	649	19.8	31.5	1190	1130	37

TABLE IV-A. OMNIDIRECTIONAL VEHICLE TESTS

Date	Drop No.	Name	T_2 (m sec.)	ΔV (ft. sec.)	Peak G Units	Onset (G sec.)	Decay (G sec.)	T_1 (m sec.)
Right 45°								
12- 6-62	946	LG	590	16.5	14.3	1140	297	65
12- 6-62	947	WT	622	19.4	17.2	1770	370	62
12- 6-62	949	ES	719	22.2	20.0	465	2050	[illegible]
12- 7-62	[illegible]	EN	815	24.1	23.3	593	1225	64
12- 7-62	951	PS	880	26.9	26.6	693	1550	60
12- 7-62	952	AR	922	27.8	24.1	1270	[illegible]	58
Forward Up 45°								
12-10-62	953	HG	615	17.4	13.5	1075	278	63
12-10-62	954	MS	655	20.1	16.4	1310	432	58
12-11-62	955	PE	731	22.8	20.4	453	1100	69
12-11-62	956	CK	813	24.4	23.8	585	1640	63
12-12-62	958	ES	666	26.0	[illegible]	594	1800	61
12-12-62	959	WT	894	28.1	22.1	1190	760	58
Left 45°								
12-14-62	960	CM	600	16.5	14.9	1070	261	67
12-14-62	961	RR	635	18.5	16.5	1350	359	60
12-14-62	962	CT	756	22.2	19.6	470	1070	68
12-17-62	963	EN	[illegible]	23.7	23.1	555	1360	64
12-17-62	964	HG	845	25.1	25.4	625	1635	60
12-17-62	965	MS	915	27.6	23.3	1330	615	58
Left 45° Up 45°								
12-18-62	967	AR	599	16.4	13.6	1050	272	67
12-18-62	968	TE	642	18.5	17.2	1300	395	60
12-19-62	969	CX	766	22.2	19.6	426	815	71
12-19-62	970	LG	813	24.5	23.4	571	1110	64
12-20-62	971	CT	878	26.1	25.5	750	1790	59
12-20-62	972	FE	925	27.4	21.4	1380	765	56
Right 45° Up 45°								
12-26-62	973	CF	576	16.6	14.2	1180	259	70
12-26-62	974	WL	628	18.2	16.0	1230	388	59
12-27-62	975	CF	745	22.1	20.6	480	860	70
12-27-62	976	WL	800	24.9	22.6	573	1370	63
12-28-62	977	MN	885	25.1	25.9	710	1670	60
12-28-62	978	RR	920	27.5	22.6	1136	685	59
Right 90°								
3-18-63	1044	LR	591	15.8	13.4	957	257	68
3-18-63	1045	BM	636	17.5	16.3	1160	355	63
3-18-63	1046	MO	758	21.6	17.7	386	1040	71
3-22-63	1047	EN	819	25.2	21.2	493	1180	68
3-22-63	1048	PE	874	27.0	22.4	600	1490	62
3-22-63	1049	HG	927	26.2	23.1	980	578	63
Left 90°								
3-25-63	1050	LG	612	17.7	13.5	750	240	75
3-25-63	1051	LN	643	20.1	17.0	1210	360	64
3-26-63	1052	FR	672	23.5	18.5	393	860	75
3-26-63	1053	CF	734	27.1	22.1	490	1160	72
3-27-63	1054	MS	840	22.6	18.8	495	1015	65
3-27-63	1055	WL	524	27.5	23.0	1210	535	64

are the same as defined in Figure 2. Δv is the velocity change or impact velocity. Table IV-B shows the omnidirectional vehicle tests gathered with respect to acceleration profiles.

RESULTS

The seven questions asked of each subject elicited the pattern and quality of comments indicated in Table V.

TABLE V. SUBJECT RESPONSES

Orientation	Acceleration Profile Number 1	2	3	4	5	6
Right 45°	none	none	a	b	c	d
Up 45°	none	e	f	none	g	none
Left 45°	h	none	none	none	none	i
Left 45° up 45°	none	none	none	j	k	none
Right 45° up 45°	none	none	none	none	l	m
Right 90°	none	none	n	o	p	q
Left 90°	none	none	r	none	s	t

a. "Slight pain" in center of forehead lasting 5 minutes.
b. "Slight pain" above left ear on skull.
c. Complained bitterly but diffusely. EKG shows abrupt rhythm changes and four premature ventricular contractions.
d. Complained bitterly but diffusely.
e. Transient pain in occiput
f. Transient pain in occiput developed severe pain in neck four hours post-test, gone in a.m.
g. Slight head pain—pain about T_2 or T_3; transient—developed severe muscle pain at point of left scapula gone 24 hours.
h. Transient pain in occiput moving to temples.
i. Mild pain radiating from right midaxillary line at level of 11th rib to left iliac crest, transient.
j. Fleeting pressure under chest belt.
k. Mild pain beneath chest strap mild pain about C8 or T1 in midline posterior.
l. "Wind knocked out."
m. "Wind knocked out."
n. Skinned right elbow.
o. Pain in right calf.
p. Pain in right calf.
q. "Knocked wind out."
r. Pain in right trapezius.
s. "Wind knocked out."
t. One premature ventricular contraction 2 minutes post-test and one 11 sec. pre-test.

The complaints listed do not indicate a tolerance end-point in any case. All subjects responded in the affirmative when asked if they would repeat the test. There was no change in pupillary or corneal reflexes after the test. The post-test blood pressures showed no con-

TABLE IV-B OMNIDIRECTIONAL VEHICLE TESTS

Date	Drop No.	Name	Orientation	T_2 (m sec.)	ΔV (ft sec.)	Peak G Units	Onset (G sec.)	Decay (G sec.)	T_3 (m sec.)
Profile #1									
12- 6-62	946	LG	Right 45°	590	16.5	14.3	1140	297	65
12-10-62	953	HG	Forward up 45°	615	17.4	13.5	1075	298	63
12-14-62	960	CM	Left 45°	600	16.5	14.0	1070	261	67
12-18-62	967	AR	Left 45° up 45°	599	16.4	12.6	1050	272	67
12-26-62	973	CF	Right 45° up 45°	576	16.6	14.1	1180	259	70
3-18-63	1044	LR	Right 90°	591	15.8	13.4	957	257	68
3-25-63	1050	LG	Left 90°	612	17.7	13.5	750	240	75
Profile #2									
12- 6-62	947	WT	Right 45°	622	19.4	17.2	1770	370	62
12-10-62	954	MS	Forward up 45°	655	20.1	16.4	1310	432	58
12-14-62	961	RR	Left 45°	635	18.5	16.5	1350	359	60
12-18-62	968	TE	Left 45° up 45°	542	18.5	17.2	1300	395	66
12-26-62	974	WL	Right 45° up 45°	518	18.3	16.0	1230	388	59
3-18-63	1045	BM	Right 90°	636	17.5	16.3	1160	355	63
3-26-63	1051	LN	Left 90°	643	20.1	17.0	1210	360	64
Profile #3									
12- 6-62	949	EI	Right 45°	730	22.2	20.0	465	1050	69
12-17-62	955	PE	Forward up 45°	731	22.8	20.4	453	1100	69
12-14-62	962	CT	Left 45°	756	22.2	19.6	470	1070	68
12-19-62	969	CK	Left 45° up 45°	764	22.2	19.5	426	815	71
12-27-62	975	CF	Right 45° up 45°	745	22.1	20.6	480	860	70
3-18-63	1046	MO	Right 90°	758	21.6	17.7	336	1030	71
3-26-63	1052	FR	Left 90°	672	23.5	18.5	393	860	75
Profile #4									
12- 7-62	950	EN	Right 45°	815	24.1	23.3	590	1225	64
12-11-62	956	CK	Forward up 45°	813	24.4	23.8	588	1640	63
12-17-62	963	EN	Left 45°	865	23.7	23.1	555	1466	64
12-19-62	970	LG	Left 45° up 45°	813	24.5	23.4	571	1110	64
12-27-62	976	WL	Right 45° up 45°	800	24.0	22.6	573	1170	63
3-22-63	1047	EN	Right 90°	819	25.2	21.2	493	1180	68
3-26-63	1053	CF	Left 90°	734	27.1	22.1	490	1160	72
Profile #5									
12- 7-62	951	PS	Right 45°	880	26.9	26.6	693	1550	60
12-13-62	958	ES	Forward up 45°	866	26.0	26.0	634	1800	61
12-17-62	964	HG	Left 45°	845	25.1	25.4	625	1635	60
12-20-62	971	CT	Left 45° up 45°	873	26.1	25.3	750	1700	59
12-28-62	977	MN	Right 45° up 45°	885	26.1	25.9	710	1670	60
3-22-63	1048	PE	Right 90°	874	27.0	22.4	600	1470	62
3-27-63	1054	MS	Left 90°	840	22.6	18.8	495	1015	65
Profile #6									
12- 7-62	952	AR	Right 45°	922	27.8	24.1	1270	690	58
12-12-62	959	WT	Forward up 45°	894	28.1	22.1	1105	760	58
12-17-62	965	MS	Left 45°	915	27.6	23.3	1330	615	58
12-20-62	972	PE	Left 45° up 45°	925	27.4	21.4	1380	765	56
12-28-62	978	RR	Right 45° up 45°	920	27.5	22.6	1130	685	59
3-22-63	1049	HG	Right 90°	927	26.2	23.1	980	578	63
3-27-63	1055	WL	Left 90°	924	27.5	23.0	1210	535	64

sistent change. Urinalysis post-test showed nothing remarkable.

The electrocardiogram showed remarkable events only on the following four tests.

951 Four premature ventricular contractions one minute post-test, abrupt rhythm changes (Δv 26.9 ft./sec., peak G 26.6 units, onset 693 G units/sec.)

965 Heart rate immediately prior to impact 116/min.—heart rate, immediately post-test 36/min.—returned to 116/min. in 5 seconds (Δv 27.6 ft./sec., peak 23.3 units, onset 1330 G units/sec.)

974 Two premature ventricular contractions three minutes after test (Δv 18.3 ft./sec., peak G 16.0 units, onset 1230 G units/sec.)

1055 Premature ventricular contractions 11 sec. pre-test and 2 min. post-test (Δv 27.5 ft./sec., peak G 23 units, onset 1210 G/sec.)

Analysis of the high-speed film data indicates, in general, good restraint of the torso in all tests. It is not possible to quantify the effect of the restraint system as opposed to that of the support system. There was no objective distinction between the microballoon and rigid couches. The subjects preferred the rigid couches, but gave no clear reasons. The major factor noted in the high-speed film was the large displacements of the head within the helmet and of the helmet itself. For a variety of reasons, including muscle tension, the helmet, when unrestrained, lifted away from the vehicle during free fall and, consequently, received on impact a deceleration substantially different from that programmed. This was particularly hazardous in that the irregular surface of the helmet was prone to pivot around the lateral head supports. Because of this, a two-inch Dacron web belt was employed early in the lateral tests to restrain the helmet shell. The six-size linear system employed in the helmet, even with an optimal fit, does not achieve a coupling between head, liner, and shell which is desirable for impact accelerations. This is manifested by a rotation of the head in the liner and a rotation of the liner in the shell. From the film data it was concluded that this displacement was primarily due to lack of support in the earphone area. The earphones were removed and vinyl foam inserts substituted sufficient to achieve a contact fit in this area during and after the 3rd

test in the left 45° orientation. This modification substantially decreased all degrees of head displacement and prompted favorable comments from the subjects. The restrained helmet caused some limitation of motion of the head in the spinal axis. From the displacements seen in the high-speed film data, it can be concluded that such limitation is not desirable because it causes an exaggerated nod of the head within the helmet. This discussion is based on one hand on the general principle that preventing displacement prevents power absorption and on the other hand on the assumption that motion of the head relative to the body is undesirable because of the stress it imposes on the vertebrae.

The power density spectra of the six acceleration profiles are presented in Figure 8. According to the previous discussion, the power density spectrum is a representation of the amounts of all frequency components present in the input. It also has considerable generality in that time patterns which may be vastly different can have the same amount of various frequency components and, consequently, the same power density spectrum. This means that arbitrary time patterns which are only approximately comparable by means of fitting with triangles and trapezoids can be reduced to the common denominator of the power density spectrum. In particular, it is possible that the development of tolerability standards in terms of power density spectra, such as reported here, may eventually enable the characterization of an arbitrary acceleration pattern with regard to tolerability by the process of finding its power density spectrum and comparing it to the standards.

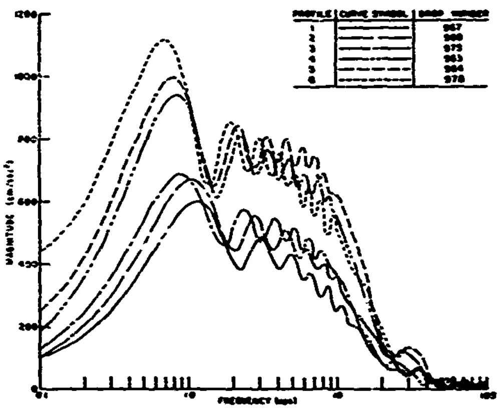

Fig. 8. Power density spectra.

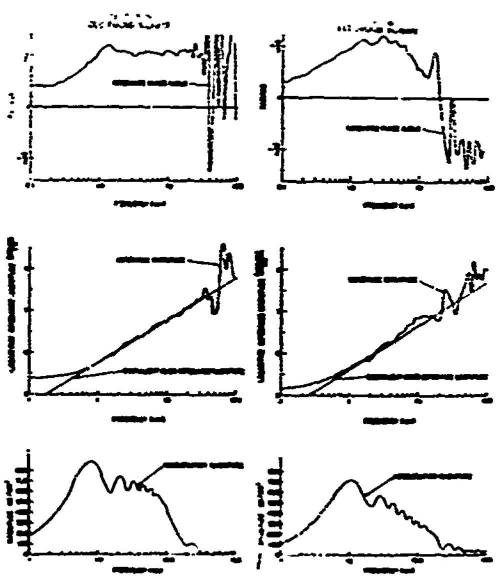

Fig. 9. Mechanical response analysis.

A typical analysis result is shown in Figure 9. This figure contains plots of the magnitude of the Fourier Transforms of acceleration, impedance (natural logarithm), and the impedance (natural logarithm) of a mass equivalent to the subject. The phase angle of the impedance is also plotted. The abscissa is a logarithmic frequency scale.

Although the results of this analysis are preliminary and extensive verification has not been completed, several trends have emerged. The impedance magnitude deviates slightly from the impedance magnitude of an equivalent mass. The phase angle of the impedance also deviates slightly from 90°, particularly at the resonances specified below, again indicating that the mass has predominated. Broad, low resonances occur at approximately 3.5, 5.5, 7.2, and 11.7 cycles per second. There is no gross distinction in the impedance magnitude nor in the phase angle among the various orientations studied.

These results indicate that the subject impedance increases approximately linearly with frequency up to about 35 cycles per second. This analysis is not valid beyond this point because the velocity pulse does not contain significant components beyond 35 cps. These results mean that for a given magnitude of acceleration input, the subject will absorb more power from the higher frequency components. In fact, since the phase angle is close to 90°, the subject has not dissipated very much power but most of that which is dissipated is at the higher frequencies. Therefore, on this basis it may be said that it is desirable in impact protection to attenuate high-frequency components of the acceleration pulse.

SUMMARY

The results of this testing indicate a set of impact conditions which are tolerable. The tests have been performed in such a way as to have a maximum of generality. The influence of the restraint system and the helmet are quantitatively unknown factors.

There is considerable indication that the head will present a problem in tolerance to impact acceleration patterns as more severe exposures are investigated. There is, however, no basis in these results for a forecast of any probable or absolute injury level.

Preliminary results of a mathematical analysis have been presented, and the trends indicate that it is desirable to attenuate high-frequency components of the acceleration pulse in impact protection.

The power density spectrum of the input accelerations have been presented and discussed as a method of approaching the problem of determining the tolerability of an arbitrary acceleration pattern.

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